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TITLE HIGH-FREQUENCY CAVITY APPLICATIONS AND MEASUREMENTS OF HIGH-TEMPERATURE SUPERCONDUCTORS

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HIGH-FREQUENCY CAVITY APPLICATIONS AND MEASUREMENTS OF HIGH-TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

A potentially important application of high-temperature superconductors will be high-frequency accelerating cavities. Currently these materials are not competitive with Nb at liquid helium temperature or with Cu at room temperature. However, available data on high-quality single crystals suggest that the relatively poor rf properties (high surface resistance and low surface magnetic field) of bulk and film specimens are due to materials properties that can be eliminated by improved processing techniques. Recent progress in the fabrication of thin films, for example, demonstrates that this is indeed the case.

1.0 INTRODUCTION

A potentially important application of high-temperature superconductors (HTS) is radiofrequency (rf) accelerating cavities. The present industry standard is niobium, which, because of its relatively low transition temperature (T_C = 9.3 K), must operate at or below liquid helium temperature to achieve the desired high Q values. From a cryogenics viewpoint alone it is thus obvious that HTS (T_C ~ 90 K) offers a potential advantage over conventional superconductors. However, for HTS to effectively compete with Nb it must exhibit similar properties at higher temperature--namely, low values of surface resistance (R_s) at relatively high rf power levels. These two requirements have not been simultaneously met with HTS; however, no experimental or theoretical evidence exists which would imply that they are unattainable.

Research results to date suggest that the poor high-frequency performance is attributable in part to the granular nature of these materials. That is, they are comprised of superconducting regions separated by non-superconducting grain boundaries, which may contain insulating or metallic impurities. Elimination of the grain boundaries, and, consequently, of the impurities, will certainly lower R_s, as evidenced by recent single-crystal results.[1] Of course there are many other materials-related properties, such as poor stoichiometry, inclusions, grain size, etc., that may be deleterious to high-frequency performance. Nevertheless, the essential point is that poor

[1] D. L. Rubin, K. Green, J. Gruschus, J. Kirchgessner, D. Moffat, H. Padamsee, J. Sears, Q. S. Shu, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B 38, 6538 (1988).

performance is strongly correlated with materials processing, and not with any inherent physical property Consequently, with improved materials fabrication techniques, one can realistically expect to achieve high-frequency cavity performance of HTS in the very near future.

2.0 HIGH-FREQUENCY SUPERCONDUCTIVITY: FUNDAMENTALS

The primary advantage of superconducting cavities over non-superconducting ones is that a much smaller fraction of the input power is dissipated in the cavity walls (Joule heating). Because the power dissipation increases as the square of the accelerating voltage, it is clear that Cu cavities become very inefficient and expensive at higher particle kinetic energies. Alternatively, superconducting cavities have surface resistances that are 5 - 6 orders of magnitude lower than Cu. After factoring in the increased refrigeration costs required to maintain the requisite low temperatures (typical operating temperatures are 1.5 - 2 K for Nb), there is still a net gain of a factor of several hundred in overall operating cost of the accelerator.[2] A further improvement in accelerator technology could be realized if materials with low R_s existed at relatively high temperatures. This would eliminate the need for costly liquid helium refrigeration. High-temperature superconductors ($T_C \sim 90$ K) meet this latter requirement, and, with improved processing techniques, are expected also to satisfy the first one

For a superconducting sample in a high-frequency cavity, the surface resistance, R_s, is defined by

$$P_s = \frac{1}{2} R_s H_s^2 \qquad (1)$$

where P_s represents the Joule losses per unit surface area of the sample, and H_s is the surface magnetic field In the normal conducting regime ($T>T_C$) R_s is given by the usual skin-depth formula

$$R_s = \sqrt{\frac{\mu\omega}{2\sigma}} \qquad (2)$$

where μ is the permeability, ω is the measuring frequency and σ is the conductivity. At $T<T_C$ (superconducting regime) the charge carriers condense into Cooper pairs. In the presence of a dc field these pairs carry all the current, thereby shielding the normal electrons, and resulting in zero dc electrical resistance In the presence of a high-frequency field the situation is more complicated and is most easily understood in terms of a "two-fluid model" one fluid associated with the normal conducting electrons and the other with the superconducting ones When a high-frequency field is applied, the Cooper pairs move frictionlessly They do, however, have inertial mass.

2 H. Padamsee, Cornell Univ, CLNS 88/844, Presented to MIT DOE/EPRI Workshop, Salem, Massachusetts, June 22-24, 1988

therefore, forces must be applied to cause the reversal of their motion. These forces are related to electric fields which must exist in the skin layer of the superconductor. Thus normal electrons are continually accelerated and decelerated which leads to dissipation (Joule losses). The analytic expression which describes the surface resistance for a classical superconductor is[3]

$$R_S(\omega, T) = A\frac{\omega^2}{T}\exp[-\frac{\Delta(T)}{k_B T}] + R_{res} \qquad (3)$$

where $\Delta(T) = \alpha k_B T_C$ and $\alpha = 1.7 - 2.3$. R_{res} is a temperature-independent resistance which depends upon the quality of the material surface. Figure 1 depicts $R_S(T)$ for Nb_3Sn ($T_C = 18$ K) taken at a frequency $\omega = 8$ GHz, and clearly illustrates the behavior described by Eq. (3). Formally, BCS theory yields a result for R_S that is similar to Eq. (3), but includes other material parameters such as London penetration depth, coherence length, and electron mean free path.

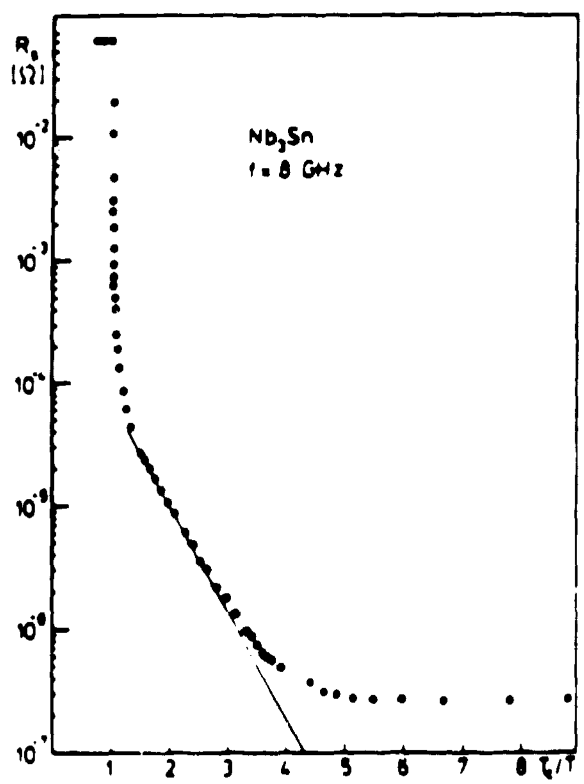

Figure 1 Surface resistance of Nb_3Sn (T_C=18 K) taken at 8 GHz The straight line is proportional to $\exp(-\frac{\Delta(T)}{K_B T})$ Taken from Ref 3

3 H Piel M Hein N Klein, A Michalke G Muller and L Ponto Physica C **153-155** 1604 (1988)

Of equal importance in the application of HTS to accelerators is the critical surface magnetic field H_s. This parameter determines the maximum accelerating voltage attainable before breakdown of superconductivity occurs. The numerical value of H_s is not equal to H_{c1} (lower critical magnetic field) as might be expected. For high frequencies it is possible for the Meissner state to exist in magnetic fields higher than H_{c1}, a field referred to as the superheating magnetic field, H_{sh}. This results from the fact that a finite amount of time is required for a vortex to nucleate.[4] For Type II superconductors near H_{c1} the time is $\sim 10^{-6}$ sec, whereas the high-frequency period is $\sim 10^{-8}$ sec. For extreme Type-II superconductors, theory predicts that $H_{sh} \sim 0.75\ H_c \gg H_{c1}$, where H_c is the thermodynamic critical field. In Nb and Nb_3Sn critical fields greater than H_{c1} have indeed been measured.[4] In the case of Nb, H_c is 2000 Oe, which corresponds to an accelerating field of ~ 50 MV/m.[5] H_c for $YBa_2Cu_3O_7$ (YBCO) has been estimated to be as high as 27,000 Oe,[6] corresponding to a maximum accelerating field of 400 MV/m! Unfortunately, thermal breakdown is not the only impediment to attaining high electric fields in superconducting cavities. Generally, field emission loading and multipacting limit the maximum accelerating field to values much lower than those determined by H_{sh}.[7] Preliminary measurements of electric-field breakdown and secondary electron emission in HTS materials have been made.[8]

3.0 CHARACTERIZATION TECHNIQUES

Surface resistance is the HTS high-frequency parameter most frequently measured; its value determines the potential of these materials for use in accelerating cavities. There are, however, many more research groups producing HTS samples than are measuring R_s, and a backlog of samples usually exists. It is important to determine which available specimens are likely to yield low values of R_s. The more conventional solid-state techniques do not necessarily provide this answer. For example, dc resistance determines the minimum percolative path of the bulk material but does not provide much information about the surface properties--a sharp resistive transition does not imply a low value of R_s. Thus, it is necessary to screen HTS material, be it bulk, film, or single crystal, so that time is not wasted on measurements of poor quality specimens. Ideally, these screening

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4 T. Yogi, G. J. Dick, and J. E. Mercereau, Phys. Rev. Lett. **39**, 826 (1977)

5 H. Padamsee, Cornell Univ., CLNS 88/864, Presented to 1988 LINAC Conference, October, 1988

6 T. K. Worthington, W. J. Gallagher, and T. R. Dinger, Phys. Rev. Lett. **59**, 1160 (1987)

7 G. Muller, M. Hein, N. Klein, H. Piel, L. Ponto, U. Klein, and M. Peiniger, Presented to European Particle Accelerator Conference, Rome, June 7-11, 1988

8 Varian Corp., private communication

techniques will be quick, simple, and inexpensive. Two measurement methods have emerged that satisfy the above-stated criteria, eddy current[9] and thermally stimulated luminescence.[10]

The eddy-current apparatus, shown schematically in Fig. 2, consists of a split coil connected to a resonant (~ 20 MHz) tank circuit of fixed capacitance. When an HTS sample (bulk, film, or crystal) is introduced between the coils, eddy currents are induced in it which modify the mutual inductance of the resonant circuit. The magnitude of the induced eddy currents depends on the conductivity of the sample, which, in turn, depends on the temperature.

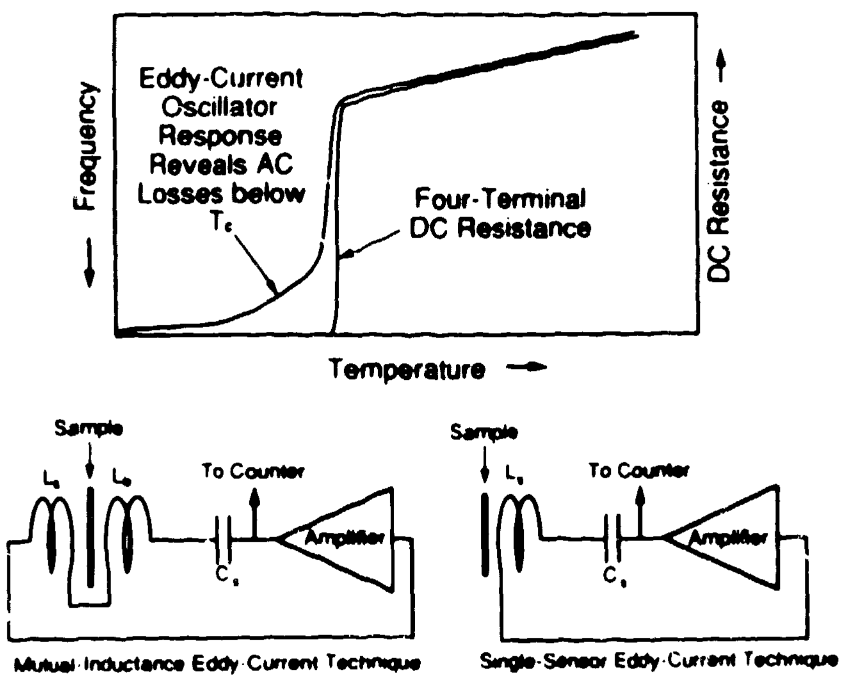

Figure 2. Schematic of eddy-current apparatus showing both the split-coil and single-coil configurations. Upper portion shows comparison between typical eddy-current and dc resistance data.

A plot of the resonant frequency vs. temperature produces a curve similar to the one shown in Fig. 2. The data are acquired in ~1 hr by the computer-controlled system. A principal advantage of the technique is that no electrical contacts are required for the measurement, this is especially important for thin films. Above T_C the technique probes a sample volume comprised of the surface area, A_s, and depth, δ, given by the normal skin-depth equation

9 J. D. Doss, D. W. Cooke, C. W. McCabe, and M. A. Maez, Rev. Sci. Instrum. 59, 659 (1988). J. D. Doss, D. W. Cooke, P. N. Arendt, M. Nastasi, R. E. Muenchausen, and J. R. Tesmer, Superconductor Sci. and Tech. To be published.

10 D. W. Cooke, M. S. Jahan, J. L. Smith, M. A. Maez, W. L. Hults, I. D. Raistrick, D. E. Peterson, J. A. O'Rourke, S. A. Richardson, J. D. Doss, E. R. Gray, B. Rusnak, G. P. Lawrence, and C. Fongang, Appl. Phys. Lett. 54, 960 (1989).

$$\delta = \sqrt{\frac{2}{\mu\omega\sigma}} \qquad (4)$$

where μ is the magnetic permeability, ω is the measuring frequency, and σ is the electrical conductivity. In the superconducting state ($T<T_C$), the volume consists of A_S and the magnetic field penetration depth, $\lambda(T)$, given by the empirical formula

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}} \qquad (5)$$

where $\lambda(0)$ is the penetration depth at T=0, taken to be 1500 - 1900 Å.[11] The essential feature is that the technique is probing the surface region, which is also the region of interest in the high-frequency measurement.

A second useful screening technique is thermally stimulated luminescence (TSL). The basic utility of the method lies in the fact that only insulators, and not metals, luminesce. Therefore, if insulating impurities such as metal carbonates and oxides exist within ~ 1μm of the superconducting surface, they will, upon excitation, exhibit TSL. These impurities, which result from improper processing of the material, contribute to high values of R_S, and, consequently, must be removed from the HTS surface. Because HTS materials are opaque with relatively large absorption coefficients (10^4 - 10^6 cm^{-1}), the TSL photons emanate from with ~ 1μm of the surface, which is precisely the region that determines R_S.

Experimental equipment for TSL measurements consists of a heater and photomultiplier tube enclosed in a light-tight box. A high-voltage power supply and amplifier control the signal, which can be plotted on an x-y recorder. Excitation can be done with x- or γ-radiation without any harm to the superconducting properties. A typical readout time is ~ 85 sec. Interpretation of the results is straightforward, if any TSL signal is observed it must be coming from insulating impurities residing near the surface, and these must be removed if low values of R_S are to be achieved. We have used this method to screen bulk, single-crystal, and in some cases, films of HTS material to estimate R_S. A quantitative correlation of R_S with TSL for bulk specimens is given in Fig. 3.[12]

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[11] D W Cooke, R L Hutson, R S Kwok, M Maez, H Rempp, M E Schillaci, J L Smith, J O Willis, R L Lichti, K -C B Chan, C Boekema, S P Weathersby, J A Flint, and J Oostens, Phys Rev B 37, 9401 (1988), D W Cooke, R L Hutson, R S Kwok, M Maez, H Rempp, M E Schillaci, J L Smith, J O Willis, R L Lichti, K -C B Chan, C Boekema, S P Weathersby, and J Oostens, Phys Rev B 39, 2748 (1989)

[12] D W Cooke, B Bennett, E R Gray, R J Houlton, W L Hults, M A Maez, A Mayer, J L Smith, and M S Jahan, Appl Phys Lett, submitted

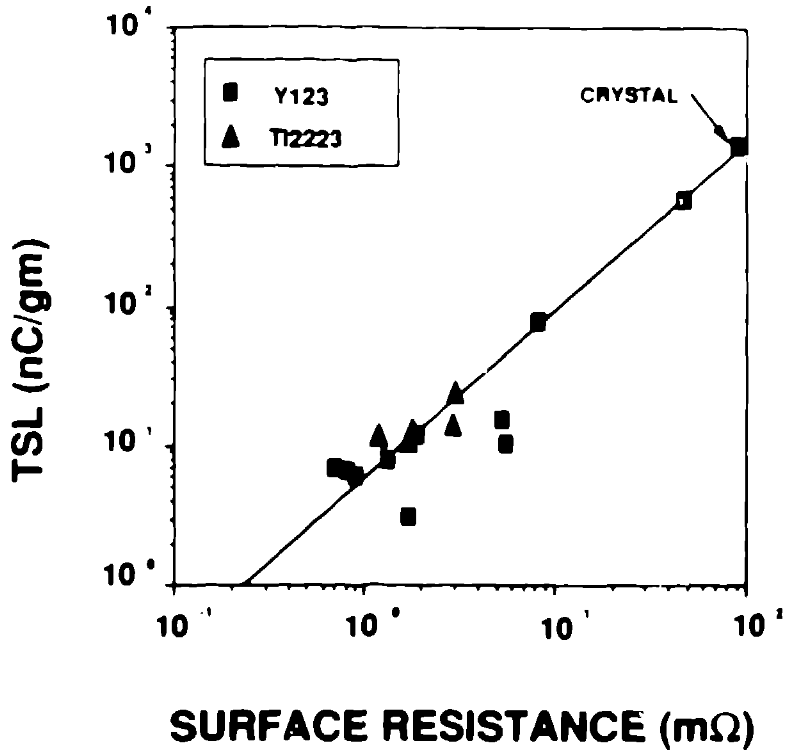

Figure 3. Correlation of TSL with R_s. Data were taken at 3 GHz and 4K on bulk specimens (except as noted).

These two screening techniques, eddy current and TSL, have proved useful in assesssing the quality of HTS for high-frequency measurements. Obviously, a great deal of time (and money for liquid helium) can be saved by screening out those samples that, for one or more reasons, are characterized by high values of R_S. Figure 4 illustrates an experimental scheme for methodically evaluating a large number of HTS samples.

4.0 SURFACE RESISTANCE AND CRITICAL FIELDS

Several techniques for measuring R_s are presently in use. These include cavity perturbation,[1,13,14,15] replacement of the end wall of a cylindrical cavity with a superconducting sample,[16,17,18] half-wave resonant

[13] M. Hagen, M. Hein, N. Klein, A. Michalke, F. M. Mueller, G. Müller, H. Piel, R. W. Röth, H. Sheinberg, and J. L. Smith, J. Magn. Magn. Mat. 68, L1 (1987).

[14] D. W. Cooke, E. R. Gray, R. J. Houlton, B. Rusnak, E. Meyer, G. P. Lawrence, M. A. Maez, B. Bennett, J. D. Doss, A. Mayer, W. L. Hults, and J. L. Smith, J. Appl. Phys., submitted.

[15] S. Sridhar and W. L. Kennedy, Rev. Sci. Instrum. 59, 531 (1988).

[16] N. Klein, G. Müller, H. Piel, B. Roas, L. Schultz, U. Klein, and M. Peiniger, Appl. Phys. Lett. 54, 757 (1989).

coaxial line,[19] stripline resonator,[20] and disk resonator.[21] Each of these techniques has particular advantages and disadvantages. For example, bulk specimens are conveniently measured in a cavity by the perturbation technique (see Fig. 5), where the electromagnetic field probes all sides of the sample. This is not the most suitable method for measuring R_S of film specimens, however, because the electromagnetic field probes not only the superconducting film, but also the substrate and interface. Assuming that the electrodynamic losses in the substrate are much smaller than those in the film, and that no unusual losses occur at the film/substrate interface, R_S values can be extracted from this measurement.

EXPERIMENTAL APPROACH

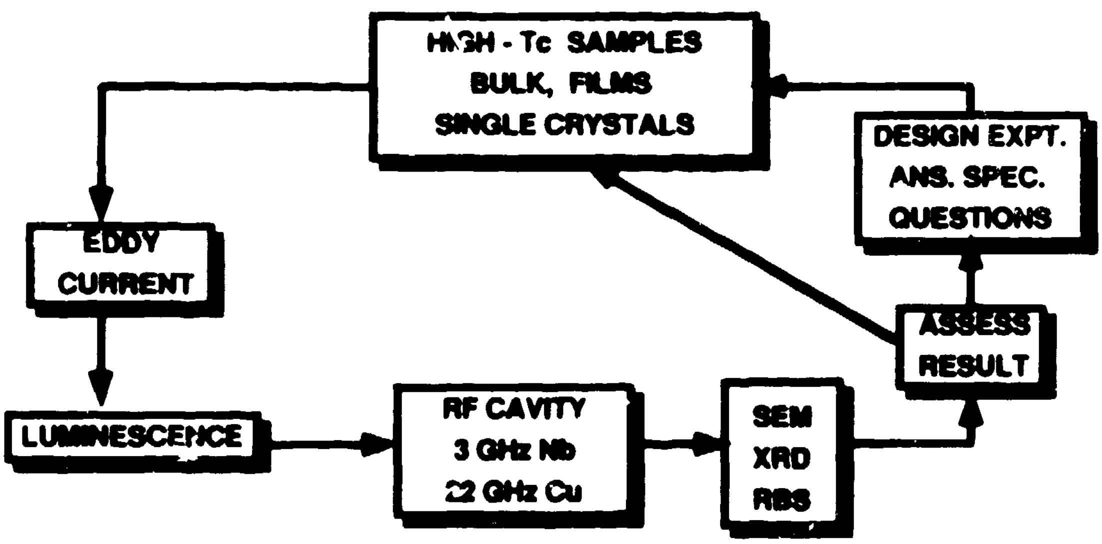

Figure 4. Experimental scheme for evaluating the quality of HTS samples.

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17 D. W. Cooke, E. R. Gray, R. J. Houlton, B. Rusnak, E. A. Meyer, J. G. Beery, D. R. Brown, F. H. Garzon, I. D. Raistrick, A. D. Rollett, and R. Bolmaro, Appl. Phys. Lett., submitted.

18 J. P. Carini, A. N. Awasthi, W. Beyermann, G. Grüner, T. Hylton, K. Char, M. R. Beasley, and A. Kapitulnik, Phys. Rev. B **37**, 9726 (1988).

19 J. R. Delayen, K. C. Goretta, R. B. Poeppel, and K. W. Shepard, Appl. Phys. Lett. **52**, 930 (1988).

20 M. S. DiIorio, A. C. Anderson, and B.-Y. Tsaur, Phys. Rev. B **38**, 7019 (1988).

21 A. Fathy, D. Kalokitis, E. Belohoubek, H. G. K. Sundar, and A. Safan, Phys. Rev. B **38**, 7023 (1988).

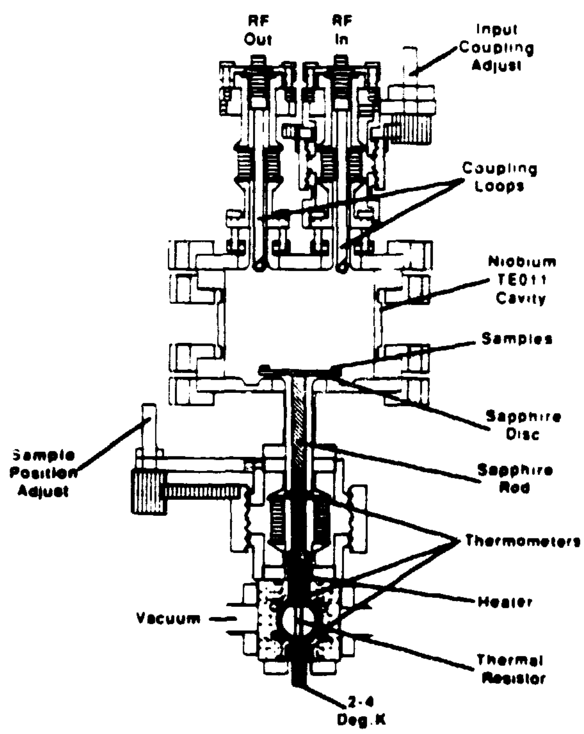

Figure 5. Schematic diagram of a 6-GHz cavity used to measure surface resistance of HTS samples. (From Ref. 1).

A more appropriate technique for measuring films is the end-wall replacement technique shown in Fig. 6. In this configuration the end wall of a cylindrical TE_{011} fundamental mode cavity is replaced by the superconducting film. For this geometry there are no microwave losses at the junction between the end wall and cylindrical body of the cavity. Moreover, the electromagnetic field distribution is easily calculated for this mode. By solving Maxwell's equations with the appropriate boundary conditions it is found that 26% of the cavity losses occur at the end wall. Thus, the reciprocal Q of the sample, $1/Q_S$, is obtained by subtracting the reciprocal Q of the empty cavity, $1/Q_C$, from that of the cavity with the sample, $1/Q_{C+S}$, i.e.,

$$\frac{1}{Q_s} = \frac{1}{Q_{C+S}} - \frac{1}{\eta Q_C} \qquad (6)$$

where η is an enhancement factor (1.26) that artificially increases the bare cavity Q to a value consistent with no losses in the end wall. The surface resistance is computed from the measured Q values of the sample and a known material, stainless steel for the system described.

$$R_s = \frac{Q'R'_s}{Q_s} \qquad (7)$$

where the primes stand for the appropriate values of the standard material (R_S' = 239 mΩ at 22 GHz).

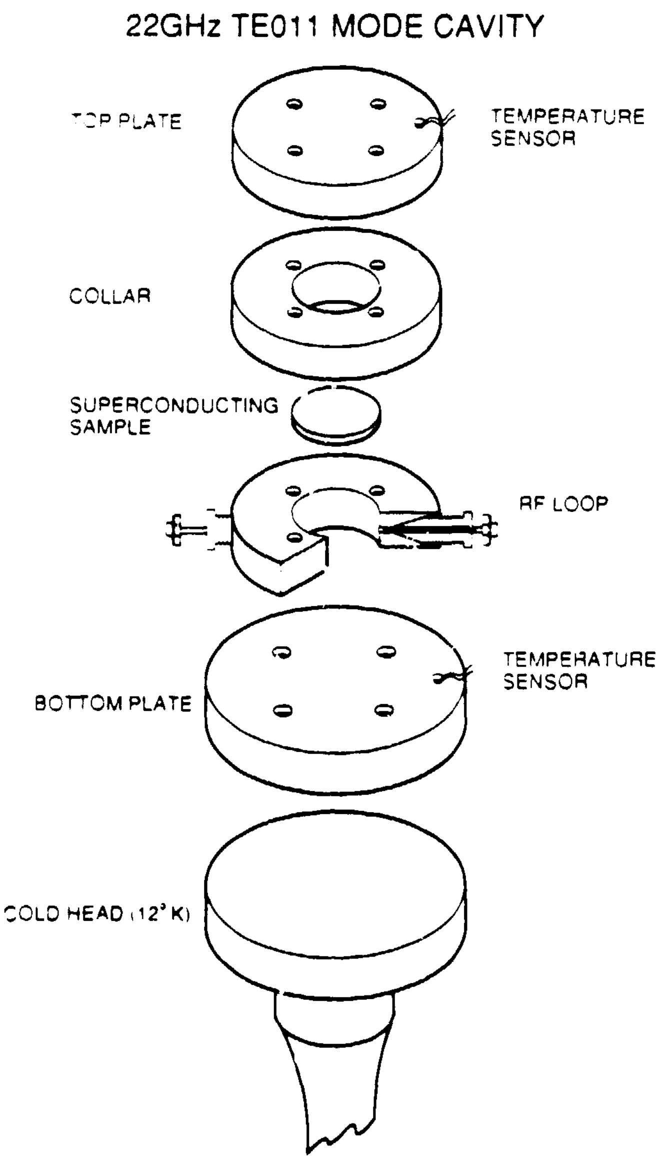

Figure 6. Schematic of a typical cavity used for measuring R_S of films. Note that the film forms the end wall of the cavity.

The temperature dependence of R_s is obtained by cooling the Cu cavity to 15 K with a closed-cycle refrigerator and slowly warming it to RT while measuring the corresponding Q values. A computer-controlled network analyzer automatically determines the resonance peak and half-power points from which the Q is calculated. The sensitivity of this Cu cavity is limited by its intrinsic Q (~ 65,000) to R_s values of approximately 2 mΩ. Lower R_s values can be obtained with the use of a superconducting Nb cavity, which has a much higher Q (~ 2 X 10^6) at 4 K.

Shown in Fig. 7 are typical surface-resistance curves for films of YBCO e-beam deposited onto $SrTiO_3$ and $LaGaO_3$ substrates, and measured in the Cu cavity shown in Fig. 6. For comparison with Eq. (3) and Fig. 1, we have plotted the data as log R_s vs. T_c/T (T_c = 90 K). Notice that there does not exist a distinct linear region in the curve of Fig. 7; For $T<T_c/2$, R_s is dominated by R_{res}, which, as discussed below, may be attributed in part to the interaction of the microwave field with the substrate. The sharp peaks observed in the $SrTiO_3$ curve are caused by the strong temperature dependence of the permittivity ε of this substrate (ε rises from near 1000 at 100 K to 25,000 at 4 K).[18] In contrast, ε for $LaGaO_3$ is ~ 25 at RT and is relatively temperature-independent.[22] Therefore no oscillations in R_s occur in films grown on this substrate.

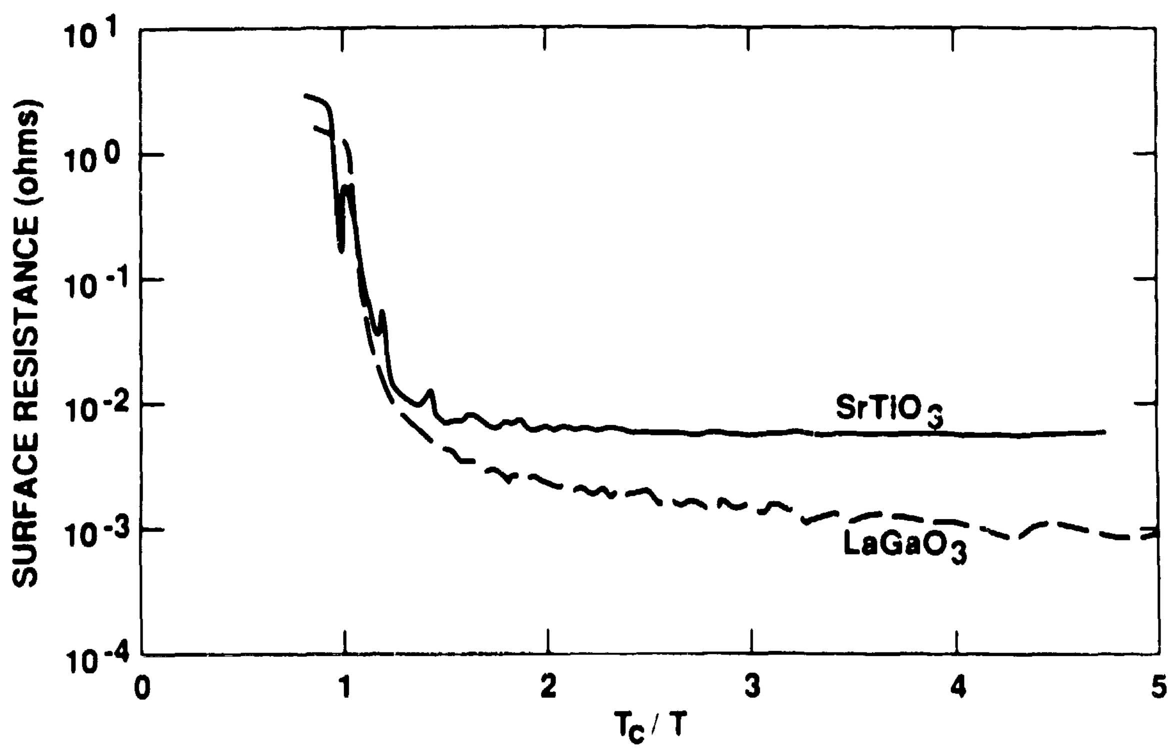

Figure 7. Surface resistance curves for YBCO films (0.8 μm) electron-beam deposited onto $SrTiO_3$ and $LaGaO_3$ substrates. Measurements were made in the 22-GHz cavity shown in Fig. 6. (T_c=90 K).

[22] R. L. Sandstrom, E. A. Giess, W. J. Gallagher, A. Segmüller, E. I. Cooper, M. F. Chisholm, A. Gupta, S. Shinde, and R. B. Laibowitz, Appl. Phys. Lett. 53, 1874 (1988).

The low-temperature value of YBCO on $SrTiO_3$ is 6 ± 2 mΩ, regardless of the thickness of the film.[17] However, similar films deposited onto $LaGaO_3$ show low-temperature values near 1 ± 2 mΩ (see Fig. 7). That is, they exceed the sensitivity of the Cu cavity and must be measured with a Nb cavity. The result of this measurement shows that the true value of R_s for the $LaGaO_3$-based film is 0.2 ± 0.1 mΩ at 4 K and 22 GHz, about a factor of two above Nb. A summary of representative R_s vs. ω data will be given later.

A primary advantage of the stripline resonator method for measuring R_s is that it can operate at different frequencies. It thus has the capability to determine R_s vs. frequency ω for the same specimen. A typical stripline resonator used at Lincoln Laboratories is shown in Fig. 8.[23] A sine wave is applied at the input, and the output is synchronously monitored with a spectrum analyzer. Resonances are observed at frequencies for which the line length l is an integer multiple of half wavelengths, i.e., $l = n\lambda/2$. A frequency range of ~ 0.5 - 20 GHz can be covered. Additionally, if the upper ground plane is comprised of the film and substrate, it is possible to obtain information on the substrate. Power measurements are also easily made with the stripline technique. A disadvantage of the technique is that it is not as sensitive as a Nb cavity unless it is an all HTS stripline resonator.

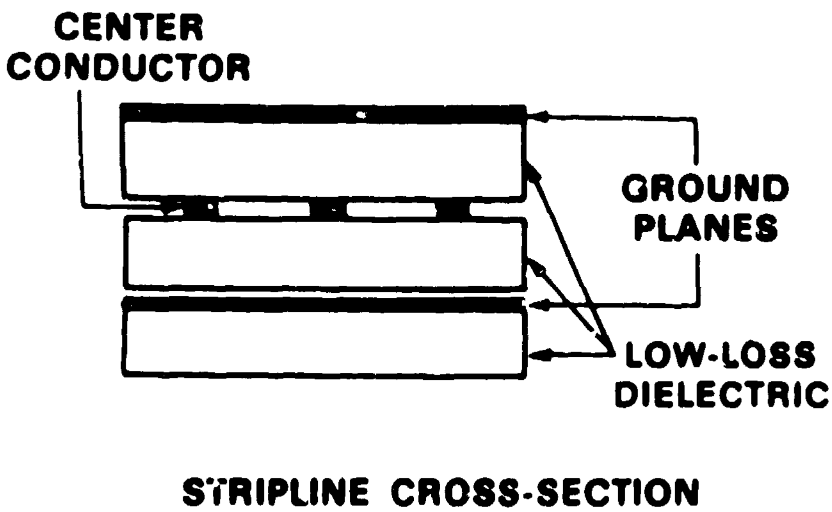

Figure 8. Typical stripline resonator for measuring R_s of HTS samples (From Ref 23)

Stripline measurements on the same $LaGaO_3$-based YBCO film that was measured in the 22 GHz Cu and Nb cavities, and described above, show that R_s is, within experimental error, similar to Nb. The particular configuration used in this experiment had the YBCO film as the upper ground plane, Nb as the center conductor and lower ground plane, and sapphire as the low-loss dielectric. $LaGaO_3$ separated the upper ground plane from

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[23] D. E. Oates, these proceedings

the Nb center conductor. Although this is not the optimum arrangement for maximum sensitivity, the R_s data do agree with the cavity measurement.

Low-frequency (150 - 450 MHz) R_s measurements on bulk superconductors are readily made in a half-wave resonant coaxial line such as the one shown in Fig. 9.[24] The outer conductor is made of Cu and the HTS sample comprises the half-wave resonant line. The entire apparatus is filled either with liquid nitrogen or helium. An advantage of this technique is that in high-power (critical field) measurements the heat generated within the sample can be easily dissipated because of its direct contact with the cryogen bath.

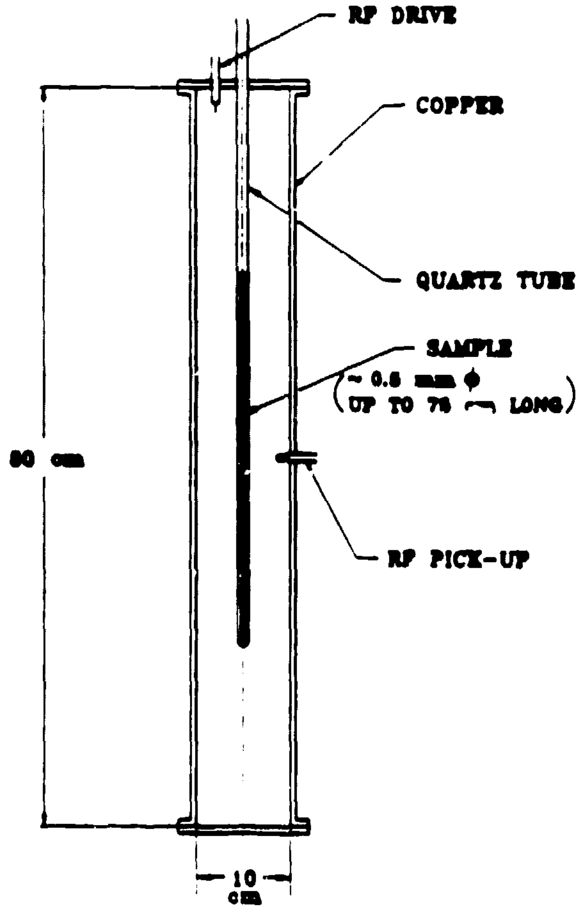

Figure 9. Half-wave coaxial resonant line used to measure R_s of HTS samples. (From Ref. 24)

During the approximately two and one-half years since the discovery of HTS, numerous laboratories have investigated the high-frequency properties of these materials. A representative collection of the laboratories

24 C. L. Bohn, J. R. Delayen, and M. T. Lanagan, these proceedings

engaged in this research, the samples measured, and best R_S results to date are given in Table 1. For comparison with Cu, Au, and Nb, selected R_S values are plotted as a function of frequency in Fig. 10.

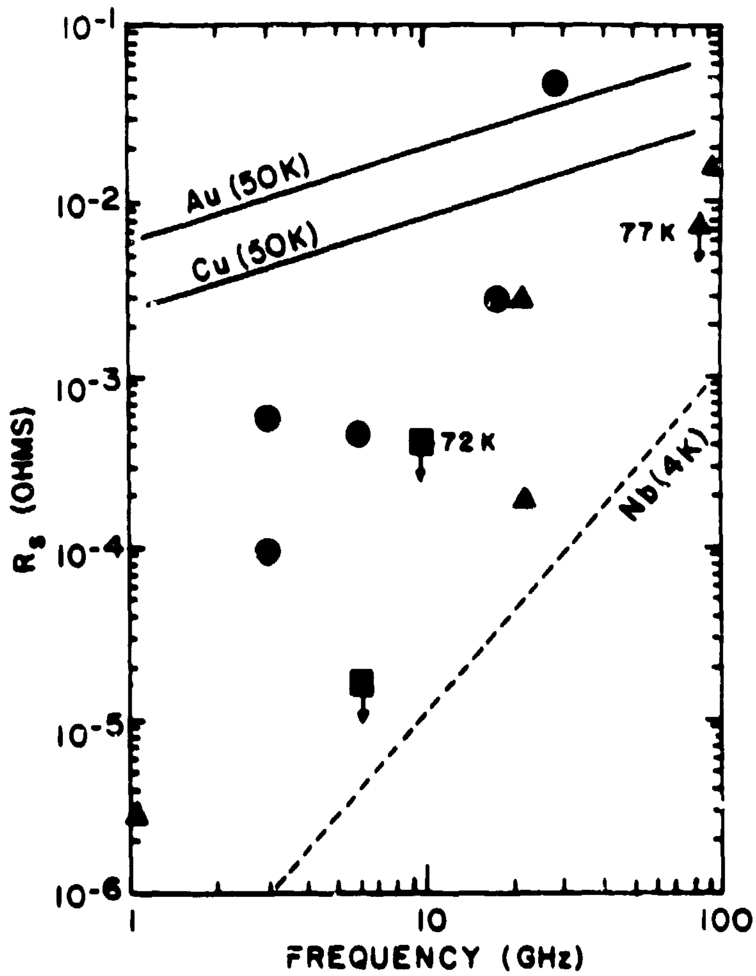

Figure 10. Surface resistance of bulk (●), film (▲), and crystal (■) HTS samples. The arrows indicate that plotted values are upper limits. Data are taken from Table 1.

The best R_s value for a bulk specimen of YBCO is ~ 0.1 mΩ (3 GHz and 4 K). This value, obtained only after repeated grinding and sintering of the material and after prolonged heat treatment, is still two orders of magnitude higher than Nb. Initial speculation was that some intrinsic property of HTS, such as zeroes of the superconducting gap on the Fermi surface, might prevent attainment of low R_s values. Single-crystal and film data clearly demonstrate that intrinsic properties are not responsible for the high values of R_s observed in bulk material. A more reasonable conclusion is that the superconducting grains are coupled by weak-link Josephson junctions, which are more prevalent in bulk than in high-quality single-crystal or film material. We reiterate the central theme: Lower values of R_s can be attained in HTS material by improved fabrication techniques.

TABLE 1
Summary of High Frequency Data

Laboratory	Frequency (GHz)	Technique	HTS Material	Lowest R_s (mΩ)	R_s(μΩ) Scaled to 1 GHz
Argonne	0.15-1.5	TEM Cu Coax	YBCO rod	$\lesssim$ 0.0011 (4.2K, 175 MHz)	$\lesssim$ 35.9
	1.5-40	TE Cu Cavity	YBCO on Ag(80 μm)	22 (4.2K, 2.65 GHz)	3130
			BSCCO on Ag (80 μm)	6.5 (4.2K, 2.65 GHz)	930
			Pb-doped BSCCO (bulk)	45 (4.2K, 29.2 GHz)	53
Cornell	5.95	TE Nb Cavity	YBCO Crystal	< 0.015 (2K, 5.95 GHz)	< 0.4
				< 0.5 (77K, 5.95 GHz)	<14.1
			YBCO (grain aligned)		
			H ∥ C	8.1 (3K, 5.95 GHz)	229
			H ⊥ C	0.45 (3K, 5.95 GHz)	13
David Sarnoff Res.	10	Disk Resonator	YBCO (bulk)	3.8 (10K, 10 GHz)	38
Japan Atomic Energy Res. Inst.	7	Monolithic TM Cavity	YBCO	$Q_u \sim 10^6$ (25K, 7 GHz)	-
Los Alamos	3	TM Nb Cavity	YBCO (bulk)	0.1 (4K, 3 GHz)	11
			BSCCO	3.3 (4K, 3 GHz)	367
			TBCCO	0.6 (4K, 3 GHz)	66
	22	TE Cu Cavity	TBCCO on MgO (5 μm)	6.5 (15K, 22 GHz)	13.4
			YBCO on $SrTiO_3$ (0.5 and 1.5 μm)	6.0 (15K, 22 GHz)	12.4
		TE Nb Cavity	YBCO on $LaGaO_3$ (0.8 μm)	0.2 (4K, 22 GHz)	0.4
Lincoln Lab	0.5-20	Micro-Stripline	YBCO on $LaGaO_3$ (0.8 μm)	< 0.003 (4.2K, 1.0 GHz)	< 3
			YBCO on YSZ	0.39 (4.2K, 0.6 GHz)	1080
NRL	18	TE Cu Cavity	TBCCO (bulk)	3 (6K, 18 GHz)	9.3
Northeastern	8	Monolithic TE Cavity	YBCO	$Q_u \sim 10^5$ (4.2K, 8 GHz)	-
	9.6	TE Pb Cavity	YBCO (bulk)	4.9 (4.2K, 9.6 GHz)	53
			LSCO (bulk)	11.3 (4.2K, 9.6 GHz)	123
	10	TE Nb Cavity	YBCO (crystal)	< 0.4 (72K, 10 GHz)	< 4
UCLA	102	TE Cu Cavity	YBCO on $SrTiO_3$ (a-axis)	300 (4.2K, 102 GHz)	29
	102		YBCO on $SrTiO_3$ (c-axis)	15 (4.2K, 102 GHz)	1.45
	148		YBCO on $LaGaO_3$ (0.5 μm)	100 (4.2K, 148 GHz)	4.6
	148		TBCCO on MgO	200 (77K, 148 GHz)	9.1
Westinghouse	10	Nb Stripline	YBCO on $SrTiO_3$ (0.5 μm) (a-axis)	4 (4.2K, 10 GHz)	40
Wisconsin	7.0-16.7	TE Cu Cavity	YBCO on $SrTiO_3$	~ 1.0 (4.2K, 8.3 GHz)	~ 14.5
Wuppertal	3-87	TM Nb Cavity	YBCO (bulk)	0.1 (4.2K, 3 GHz)	11
		TE Cu Cavity	YBCO on $SrTiO_3$ (0.6 μm)	< 8 (77K, 86.7 GHz)	< 1.1
			YBCO on $LaGaO_3$ (0.5 μm)	18 (20K, 86.5 GHz)	2.4
			YBCO on Ag (10-30 μm)	18 (77K, 21.5 GHz)	39
				< 3 (4.2K, 21.5 GHz)	< 6.5
				Copper (4K)	1200
				Niobium (4K)	0.2

Many high-frequency electronic applications of HTS require only that R_s be lower than Cu. For an accelerating cavity, however, low R_s at high power levels is required. In general, the field dependence of R_s for bulk and film specimens is strong, the superconducting state does not exist above ~ 5 Oe. In contrast, single crystal results show that the superconducting state persists for surface fields up to 93 Oe at 20 K (5.95 GHz).[1] This value is, however, far inferior to the best value achieved in Nb (1600 Oe). These results suggest that weak-link behavior may be responsible both for high R_s values and poor surface-field performance. These measurements were done in cavities where the superconducting samples were in vacuum. Owing to the poor thermal conductivity of HTS, it has been suggested that the breakdown of superconductivity, as observed in these measurements, occurs because the heat being deposited in the sample cannot be readily dissipated.[25]

Alternatively, measurements of the field dependence of R_s on bulk $YBa_2Cu_3O_7$ done in a coaxial resonator, where the sample was bathed in liquid cryogen, show that the superconducting state does not break down for fields as high as ~ 640 Oe (77 K and 190 MHz).[25] The corresponding R_s value for this surface magnetic field is 5% of the normal value. These results are encouraging and emphasize the importance of thermal conductivity in any cavity design utilizing HTS.

5.0 FUTURE PERSPECTIVES

Tremendous progress has been made in reducing R_s of HTS materials. In the approximately two years since the first R_s value of HTS was reported (YBCO bulk),[13] improved processing and fabrication techniques have led to films of 1-inch diameter that are competitive with Nb at 4 K.[17] Moreover, recent results on the power dependence of R_s suggest that, in principle, surface magnetic fields greater than 600 Oe can be attained. Thus, values of the two most important parameters that determine the suitability of HTS for cavity applications, R_s and H_s, indeed suggest that no fundamental limitation exists which should discourage further developmental work on these materials. This does not imply that these are the only problems requiring solution before an HTS accelerating cavity can be constructed. Other considerations are film thickness (determined by London penetration depth), thermal conductivity, substrate, substrate backing material, film degradation with time, radiation sensitivity, and field emission. Nevertheless, recognizing that the current status of Nb cavities has evolved over a period ~ 20 years, it is not unreasonable to expect that some research and development time will be required to make HTS cavities that are competitive with Nb.

Future improvements in HTS high-frequency properties will likely come from improved processing techniques. For example, *in situ* annealed films, as opposed to post-deposition films, yield lower values of R_s.[16] These improvements may result from better oxygenation, and/or elimination of non-reacted metals in the material. Certainly the lower annealing temperature (~ 500°C) of *in situ* processing will help to reduce the problem of

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[25] J. R. Delayen and C. L. Bohn, Phys. Rev. B, submitted.

substrate interaction with the superconductor, which commonly occurs at elevated temperatures (for example, ~ 860°C encountered in post-deposition processing).

Finally, it is noteworthy that progress to date on high-frequency HTS materials has evolved from experimental work with minimal guidance from theory.[26,27] As a better theoretical picture emerges, however, it is expected that new ideas will be infused into the experimental work leading to further improvements in high-frequency properties.

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